

ARO 13500.4-MS
16348.14-MS

(12)

AD A 129569

The Investigation of the Influence of Welding
Flux on the Pyrometallurgical, Physical and
Mechanical Behavior of Weld Metal

FINAL REPORT
CSVICWR-8301

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17 May 1983

U.S. ARMY RESEARCH OFFICE

DAAG29 76G 0143
DAAG29 77G 0097
DAAG29 78G 0052
DAAG29 79G 0066

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Investigation of the Influence of Welding Flux on the Pyrometallurgical, Physical, and Mechanical Behavior of Weld Metal		5. TYPE OF REPORT & PERIOD COVERED FINAL: 15 February 1976- 14 February 1983
7. AUTHOR(s) David L. Olson		6. PERFORMING ORG. REPORT NUMBER CSMCWN-8301
9. PERFORMING ORGANIZATION NAME AND ADDRESS Center for Welding Research Department of Metallurgical Engineering Colorado School of Mines 80401 Golden, Colorado		8. CONTRACT OR GRANT NUMBER(s) DAAG29 76 G 0143 DAAG29 77 G 0097 DAAG29 78 G 0052 DAAG29 79 C 0066
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N/A
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Department of the Army U.S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE 17 May 1983
		13. NUMBER OF PAGES
		15. SECURITY CLASS. (of this report) Not Classified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or de- cision, unless so designated by other documentation.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Welding, Flux, Arc Stability, Viscosity, Weld Metal, Penetration, Pyro- metallurgy of Welding Flux, Steel Weld Metal Microstructure, Submerged Arc Welding.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The behavior of the physical, chemical and mechanical processes associated with submerged arc welding fluxes was characterized and mechanistically modeled. Of particular interest was the utilization of manganese and calcium silicate welding fluxes to achieve high performance submerged arc steel weldments. The determination of the specific role of the ionic additions on the behavior of these welding flux systems has been achieved. This investigation established a more fundamental understanding of welding (over)		

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flux behavior from which it is anticipated that a more sophisticated methodology will result for the future development of submerged arc welding consumables for advanced engineering steels.

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1.0 Statement of Problem

This investigation is to characterize and mechanistically model the behavior of the physical, chemical and mechanical processes associated with submerged arc welding fluxes. Of particular interest is the utilization of manganese and calcium silicate welding fluxes to achieve high performance submerged arc steel weldments. With the establishment of a fundamental understanding of flux behavior, it is anticipated that a more sophisticated methodology will result for the future development of submerged arc welding consumables for advanced engineering steels.

2.0 Summary of the Most Important Results

The specific role of ionic additions on the physical and chemical behavior of welding fluxes has been investigated (16,18,19). It was necessary to characterize behavior through controlled experiments and then with these results develop meaningful correlations from which physical and chemical models can be established.

Figure 1 is a schematic of the many types of relationships which must be characterized if a comprehensive understanding of the influence of flux composition on weld integrity is to be realized. Correlations between (i) flux composition and physical behavior of the flux (ii) physical behavior of the flux and weld bead morphology, (iii) flux composition and weld metal chemistry, and (iv) weld metal

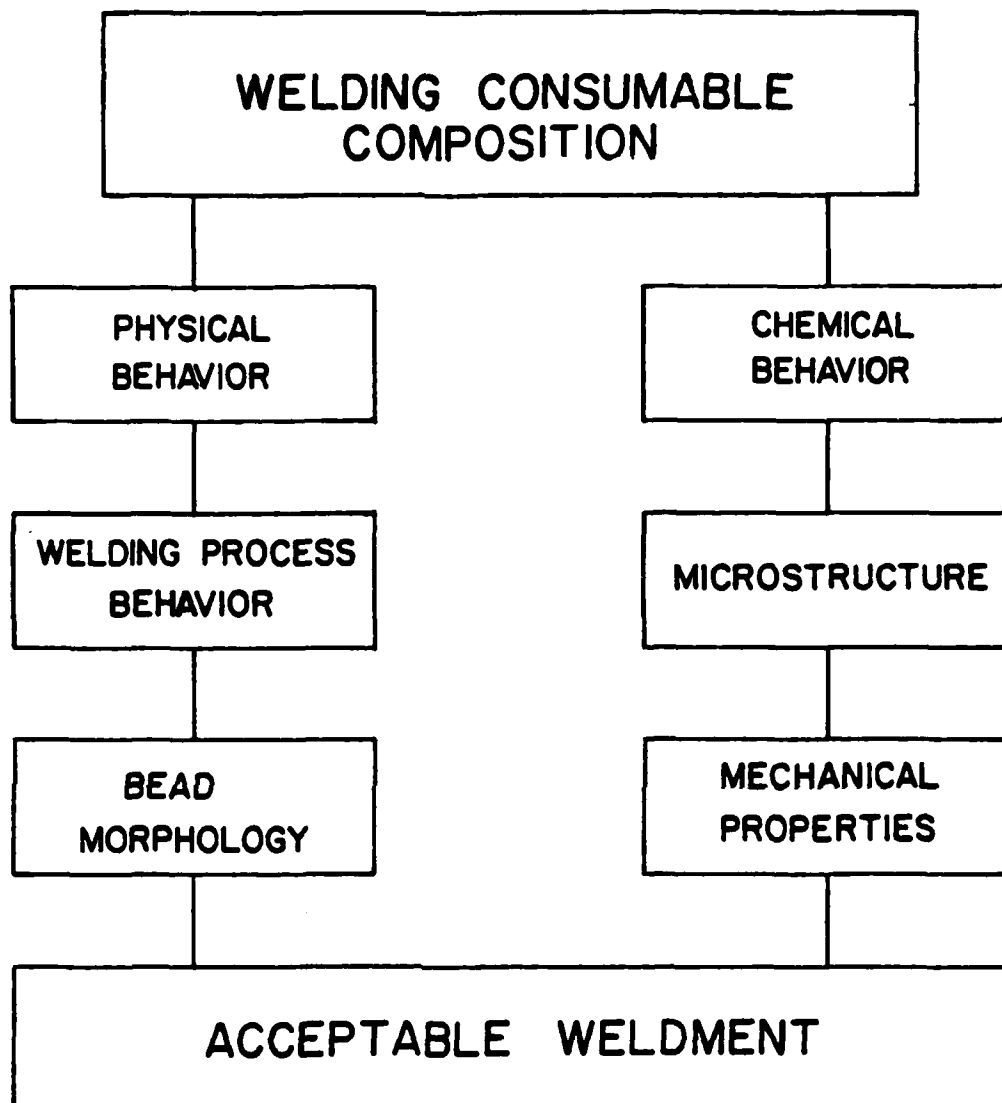


Figure 1: Physical and chemical relationships which establish an acceptable weldment from a welding consumable.

chemistry and weld metal microstructure, and (v) weld metal microstructure and weld metal properties have been achieved.

Tables I, II and III illustrate the physical, chemical and mechanical properties studied as functions of the various additions to manganese and calcium silicate fluxes. All fluxes used in this investigation were fused reagent grade chemicals.

2.1 Flux Viscosity

The viscosity of a welding flux is one of its most important properties. The flux must be fluid enough to allow the transfer of elements between flux and metal and allow gases to escape. But it must also be viscous enough to support the weld puddle. Flux viscosity is affected by both temperature and composition. The effect of small amounts of additions (up to 5 ionic percent for 14 different additions) on flux viscosity for the manganese silicate systems was studied (3,6,7,8). The viscosity was measured at 1450C which is a temperature in the range where the slag is most likely influencing a steel weldment. All the manganese-silicate fluxes had a constant SiO_2 content of 40 weight percent. Thus, the effects of the added ions are actually compared to the effects of manganese ions on the silicate network. Small additions at the concentration levels common for residuals in mineral based fluxes was found to potentially promote sufficient change in flux viscosity to degrade the designed performance of the flux. Many of the viscosity curves as function of ionic additions show viscosity minima. As the curves decrease to

TABLE I
Manganese Silicate (40% SiO₂) Submerged Arc Welding Flux

	AISI 1020 Steel (with Page mild steel wire)										AISI 1010 Steel (with Page mild steel wire)									
Multiple pass studies																				
Influence of Heat Input																				
Influence of Welding parameters																				
Weld metal mechanical properties																				
Weld metal phase transformation modeling																				
Parent metallurgical modeling																				
Weld metal chemistry																				
Weld metal inclusion characterization																				
Weld metal microstructure																				
Leachability																				
Bead morphology																				
Capillarity																				
Are Stability																				
Viscosity																				

Complete

CaO																				
CaF ₂																				
CaO-CaF ₂																				

TABLE II Manganese Silicate (40% SiO₂) Submerged Arc Welding Flux

AISI 4340 STEEL
(with Linde 4340 Wire)

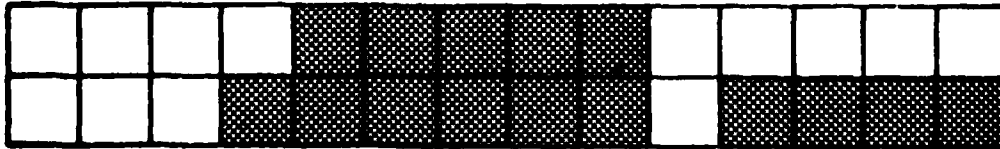
	FeO	CaO	CaF ₂	CaO-CaF ₂	Li ₂ O	Na ₂ O	K ₂ O
Multiple pass studies							
Influence of Heat Input							
Influence of Welding parameters							
Weld metal mechanical properties							
Weld metal phase transformation modeling							
Pyrometallurgical modeling							
Weld metal Chemistry							
Weld metal inclusion characterization							
Weld metal microstructure							
Detachability							
Bead morphology							
Capillarity							
Arc Stability							
Viscosity							

Completed

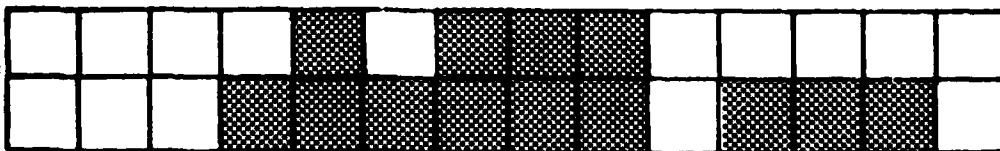
TABLE III Calcium Silicate (0-40% SiO₂) Submerged Arc Welding Flux

Niobium Microalloy
(Lukins Frostline)

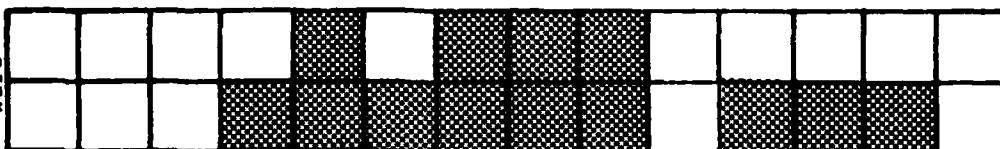
Steel wire



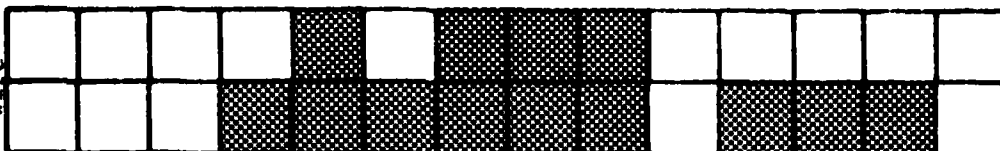
AWS-EH14
wire



AWS-E-70SG
wire



AWS-EMI
wire



- Multiple pass studies
- Influence of heat input
- Influence of welding parameters
- Weld metal mechanical properties
- Weld metal phase transformation modeling
- Pyrometallurgical modeling
- Weld metal chemistry
- Weld metal inclusion characterization
- Weld metal microstructure
- Detachability
- Bead morphology
- Capillarity
- Arc Stability
- Viscosity

Completed



CaF₂-Al₂O₃

CaF₂-Al₂O₃

CaF₂-Al₂O₃

CaF₂-Al₂O₃

their minima, network modification is occurring. Bonds in the silicate structure are being disrupted, resulting in decreasing viscosity. To the right of the minima, the interactions between an ion and the added metal cations change in a manner which results in an apparent localized network formation, and the flux viscosity increases. Attempts have been made to determine the ionic properties responsible for changes in flux viscosity. Results show that ionic radius has little effect until the ion content of the flux reaches five ionic percent. The specific valence of ionic additions has a strong effect on viscosity. Ions with high valence numbers were found likely to act as network-formers and such additions gave the flux a relatively high viscosity.

Flux viscosity is a strong function of temperature. Decreasing the temperature to about 1100C raises the viscosity to about 200 poise. It has been found that if a specific manganese silicate flux has a viscosity at 1450C larger than seven poise, there is a definite increase in the susceptibility of weld surface pocking. This pocking has also been associated with more easily reducible oxides in the flux. The oxygen is reduced and reacts with carbon to form carbon monoxide which cannot be transported through a higher viscous flux and is trapped at the liquid metal/flux interface, forming surface defects. Since viscosity is definitely influenced by temperature and thus heat input, pocking can be evidence that a submerged arc welding flux, which was designed for high current applications, is being used for too low a current or too great a travel speed.

Flux viscosity has a strong effect on weld penetration. More viscous fluxes were found to confine the weld bead and concentrate heat transfer to a smaller region of the base metal, giving deeper penetration. In all cases, penetration was found to increase with increases in viscosity (6). But other factors have also been found to influence weld penetration (13,17).

2.2 Arc Stability

Arc instability has been defined in this investigation as the deviation in arc voltage from the set welding voltage. Ionic additions (at the level of residual contamination) to the reagent grade fused manganese silicate welding flux were found to definitely alter the arc behavior. Fourteen different manganese silicate flux systems were investigated (3,6,7,8). Flux additions with greater ionization potentials were found to provide for a more stable arc stability. These results indicate that arc stability is probably controlled more by the electrode spots than by interactions in the plasma. Increasing the weld metal oxygen content increases the oxygen or oxide content on the weld pool surface which has been suggested to lower the work function at the cathode spot (17). The arc instability correlated well with weld metal oxygen content (19). For some manganese silicate fluxes the arc stability increased with weld metal oxygen and with others it decreases.

The arc instability was also analyzed as a function of weld metal oxygen content for welds made with fluxes in the $\text{CaO-CaF}_2\text{-SiO}_2$

system (27,29). For fluxes with 40% SiO_2 , the arc instability actually increased with increasing weld metal oxygen. This is just opposite of the expected behavior suggested by Patchett, et al., (17). If Patchett's model is correct, then this would suggest that some element besides oxygen may have affected the arc behavior. For this reason, plots of arc instability versus weld metal oxygen for welds made with fluxes with constant CaF_2 contents were examined. Each of these plots showed that arc instability is decreased with oxygen in agreement with Patchett's model. This seems to indicate that CaF_2 (fluorine) must also influence the arc behavior along with the oxygen.

Arc stability also affects penetration. Apparently, arc fluctuations result in more widely distributed heat transfer to the base metal, which results in decreased penetration. So more stable arcs provide better penetration (3,13,17).

2.3 Interfacial Tensions

Interfacial tensions also play a role in determining bead morphology. There are three interfacial tensions to consider in a submerged arc weld: the flux-solid metal interfacial tension (γ_{fm}^*), the flux-liquid metal interfacial tension (γ_{fl}^*), and the liquid-solid metal interfacial tension (γ_{lm}^*). Equilibrium force balances, which were applied at the weld bead triple point, were used to derive equations from which the relative values of two of the interfacial tensions were calculated (3,6,7,8). It was assumed that γ_{lm}^* is constant, since none of the ions from the flux are expected to be

active at that interface. This assumption eliminates one variable and allows the use of the force balance equations to calculate the values of γ_{fl} and γ_{fm} relative to γ_{lm} . If the term γ_{fl} is large, the weld bead will tend to minimize its surface area. Heat flow into the base metal will then be more concentrated and deeper penetration would be expected. If γ_{fm} is relatively large, the molten bead will spread out in an attempt to minimize the flux-solid metal interfacial area. Heat flow into the base metal will be more diffuse and less penetration should result. Penetration was found to be directly related to γ_{fm} and γ_{fl} for steel welds made with manganese silicate welding fluxes (3,6,7,8).

2.4 Weld Penetration Equation

The separate effects of flux viscosity, arc stability, and interfacial tensions on penetration have been demonstrated. But in reality, these variables are at work simultaneously. In order to illustrate their combined effect more clearly, all three variables were included in an equation which related them linearly to weld penetration, P:

$$P = K (\gamma_{fl} - \gamma_{fm}) N (30 - V) + C \quad (\text{Eq. 1})$$

where N is the flux viscosity, and ΔV is the variation in voltage around the set welding voltage, 30 volts. This expression described the influence of the flux behavior at constant welding parameters (13).

Penetration correlated well with this expression for AISI 1020 and 4340 steel welds made with 14 different manganese silicate welding flux systems (17). This work does, however, suggest a modified and more comprehensive Jackson-Shrubsall equation of the general form (16):

$$P = K'' (\gamma_{f1}^+ - \gamma_{fm}^+) N \Delta V (I^4/SV^2)^{1/3} + C \quad (\text{Eq. 2})$$

Patchett, et al., (17) also interpreted these penetration results and promoted an oxygen model to explain the submerged arc weld penetration behavior. They suggested that cathodic electron emission from the weld pool is strongly influenced by the oxygen activity. The oxygen activity of the cathode surface is directly related to the weld metal oxygen content and indirectly related to the flux composition. Their model suggests that increasing the weld metal oxygen content should decrease the arc instability and increase penetration. Applying their model to our results of manganese silicate flux systems, it was found that penetration correlated very well with weld metal oxygen content. But for some flux systems, penetration increased and for other systems it decreased with increasing weld metal oxygen content. The CaF_2 and Li_2O additions to manganese silicate fluxes promoted behavior which are inconsistent with the suggested trends of the Patchett model.

The variation of weld penetration with oxygen content in the weld metal was measured for welds made with $\text{CaO-CaF}_2\text{-SiO}_2$ welding flux (22,29). The constant silica plots show diverse effects. The 40%

silica flux welds showed an increase in penetration with weld metal oxygen content. No oxygen effect could be observed in the 20% silica flux welds, while a decreasing penetration with increasing oxygen was seen for the constant 10% silica fluxes. Penetration variation with weld metal oxygen at a constant CaF_2 content was analyzed and showed the trend of increasing penetration with increasing weld metal oxygen. It has also been found that the flux with CaF_2 additions correlated penetration with weld metal nitrogen in the manner predicted by Patchett, et al., (17) for oxygen.

2.5 Slag Detachability

Slag detachability for various manganese silicate flux systems was measured and compared on a relative scale (7). Alkaline earth additions (up to 3 ionic percent) were found to have promoted excellent slag detachability. Zn, Ti and Cr ionic additions (up to 5 percent) gave poor detachability. The other transition metal oxide additions to a manganese silicate flux indicated acceptable slag detachability.

2.6 Relationship of Low Carbon Steel Weld Metal Microstructure of Weld Metal Oxygen Content

Even though we expect the oxygen content of wrought steel to be below 100 ppm oxygen, the very lowest weld metal oxygen levels for flux-related welding processes are in the range of 200-300 ppm. Manganese silicate submerged arc welding fluxes were found to produce

a high weld metal oxygen content, up to 900 ppm oxygen for binary MnO-SiO₂ eutectic compositions (20). New submerged arc welding fluxes based on lower silicon contents, usually with a substantial CaF₂ addition, have been developed to promote lower weld metal oxygen content and thus higher weld-metal toughness (22). Figure 2 illustrates the large variations in weld metal oxygen content with both FeO and CaF₂ additions to manganese silicate and with the calcium silicate flux systems. Notice the major reduction in weld metal oxygen contents for calcium silicate fluxes compared with manganese silicate fluxes of the same silica content, and the further decrease with the introduction of CaF₂ additions. Figure 2 illustrates the weld metal oxygen range studied in this investigation.

Fluxes with less than ten percent silica were found to be insufficient in silica network to be stable as a glass phase on cooling. These low silica fluxes can crystallize and lose much of their effectiveness as a protective slag. During cooling, these slags degraded into a fine powder, and the welds made with these powders showed irregular bead shapes and severe porosity (19).

A basicity index, which is a index for the classification of oxide slags as to their ability to refine sulfur from steel, has been used to predict weld metal oxygen content. Weld metal oxygen contents were measured in this investigation for direct current-electrode positive (DCEP) submerged arc welds made by a variety of reagent grade manganese silicate fused fluxes. These measurements were made to test the validity of using the basicity index to predict weld metal oxygen

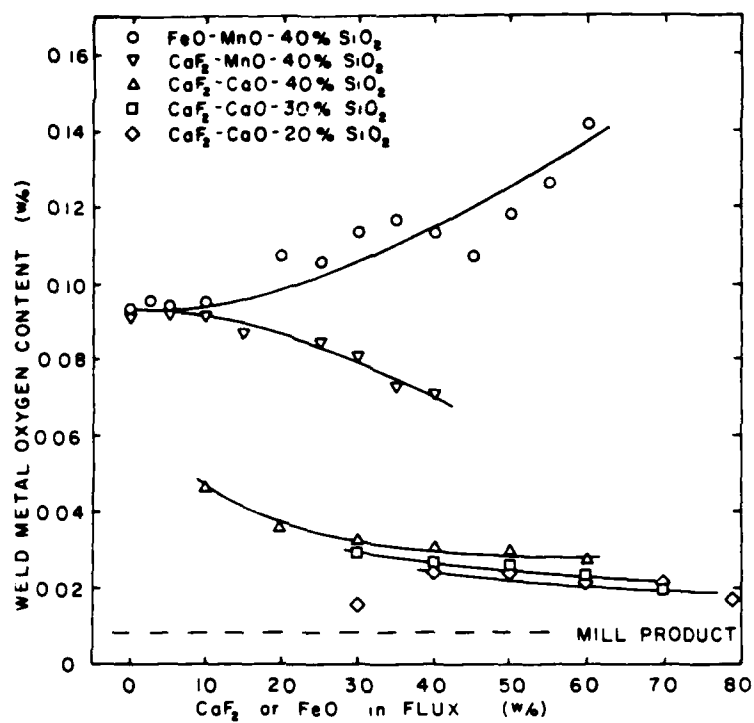


Figure 2: Effect of CaF_2 and FeO additions to flux on the weld metal oxygen content.

content (19). It was found that weld metal oxygen content-basicity index correlations are not very predictable, especially if there is a sufficient content of transition metal oxide addition in the flux. It is anticipated that the basicity concept can be correlated to weld metal oxygen content only when there are variations in the silica content of the flux and the fluxes are made up with a very limited transition metal oxide content. A better index for weld metal oxygen content would be a ratio of the stable oxide contents to the less stable oxides. The stability of the oxides can be based on their relative position on the Richardson free energy of formation plot.

2.7 Pyrometallurgical Behavior of Welding Fluxes on Welding Low Carbon Steels

Studies have been undertaken to develop analytical methods to predict the steel weld metal composition resulting from a specific wire and flux by applying pyrometallurgical thermodynamic concepts based on the assumption of the existence of a pseudoequilibrium state (24). The usual approach is to assume that a state of thermodynamic equilibrium is attained or approached, on the basis that the high temperatures and high surface-to-volume ratio counteract the short time available for these reactions to go to completion.

The weld metal oxygen and carbon content has become a primary interest. This investigation has found a correlation between weld metal carbon and oxygen content for specific manganese silicate flux

systems (20). The finding indicates that on mixing oxide additions which have a very stable metal oxygen bond (an oxide from the lower regions of the Richardson chart) to fused manganese silicate fluxes results in a carbon monoxide type reaction results. This carbon monoxide reaction is suggested since the product of weld metal carbon and oxygen contents was found to be a constant. This type of reaction was not observed for oxide additions from the top region of the Richardson chart.

This investigation also has demonstrated the utility of using thermodynamic calculations to predict weld metal manganese and silicon contents in submerged arc welds made with reagent grade $\text{SiO}_2\text{-MnO-FeO}$ fluxes. The selection of this flux system has been based on the fact that the same elements encountered in the flux can also be seen in the slag and steel. Controlling pyrometallurgical mechanisms for controlling the weld metal silicon, manganese, and oxygen contents have been suggested (24).

Thirteen reagent grade fused $\text{SiO}_2\text{-MnO-FeO}$ fluxes were made with the SiO_2 held constant at 40 weight percent and MnO replaced systematically by FeO at 5 weight percent addition intervals until completely replacing the MnO with 60 weight percent FeO addition. All welds were made with constant welding parameters and thus the same heat input. Examination of the weld metal chemistries shows a constant silicon pickup by the weld metal of approximately 0.08 weight percent, independent of the amount of iron oxide addition to the flux. The weld metal oxygen content, however, increases continuously from

about 0.092 weight percent, at the SiO_2 (60 wt%)- MnO flux composition, to approximately 0.15 weight percent when all the MnO is replaced by the FeO . These results suggest that the weld metal silicon content is not controlled by the amount of weld metal oxygen. The constant silicon level was reported to be due to a very rapid reaction involving gaseous components, such as silicon monoxide which is present at a constant activity (24). The SiO vapor is only stable at high temperatures, and one way that it could be generated is by the SiO_2 reacting with manganese vapor.

A "neutral point" which corresponds to the point where there is no net manganese transfer (thus the amount of manganese oxide in the slag should be the same as that in the flux) has been determined. The slag composition at this neutral point has been determined and is found to be 23wt% FeO , 37wt% MnO and 40wt% SiO_2 or in terms of mole fractions 0.212 for FeO , 0.346 for MnO and 0.442 for SiO_2 .

Assuming that the controlling chemical reaction for the weld metal oxygen is given by the following equation:



A equilibrium constant can be expressed as:

$$K = \frac{[\text{O}]}{\gamma_{\text{FeO}} N_{\text{FeO}}} \quad (\text{Eq. 4})$$

where ($N_{\text{FeO}} = 0.212$), the activity coefficient of iron oxide, γ_{FeO} , is equal to 0.7, and the oxygen in the weld at the neutral point was $[\text{O}] = 0.1005 \text{ wt.}\%$). The equilibrium constant becomes 0.677 for these conditions. Determination of an approximate effective temperature of the chemical reaction from the known temperature dependence for the equilibrium constant was also performed. The effective reaction temperature was found to be 1900C.

The silicon content in a low carbon steel weld metal showed both positive and negative deviations for the $\text{CaO-CaF}_2\text{-SiO}_2$ flux system (22,29). When the SiO_2 content is approximately equal to the CaO content, no silicon loss is observed. Above that region, $\% \text{SiO}_2 / \% \text{CaO}$ greater than 1, there was an increase of silicon in the weld pool indicating that silicon was transferred from the flux to the weld. When $\% \text{SiO}_2 / \% \text{CaO}$ is less than 1, a silicon loss was seen. This behavior is explainable from known silica activity data. The weld metal manganese for low carbon steels was found to remain constant with large variations in the composition for the $\text{CaO-CaF}_2\text{-SiO}_2$ flux system. The results for the $\text{CaO-CaF}_2\text{-SiO}_2$ system were compared with the $\text{MnO-CaF}_2\text{-SiO}_2$ flux system.

2.8 The Influence of Weld Metal Oxygen on Low Carbon Steel Weld Metal

This investigation studied the relationship between weld metal microstructure and the composition of fused manganese silicate submerged arc welding fluxes; in particular, (40%) SiO_2 - MnO-FeO and

(40%) SiO_2 - MnO - CaF_2 fluxes (21). The manganese silicate system was chosen since it is known to produce very high weld metal oxygen content. These high oxygen contents are very useful in illustrating the nature of oxide inclusions in steel weld metal. The FeO additions (0 to 60%) were found to increase the oxygen (900 to 1500 ppm) and decrease the weld metal manganese content (1.05 to 0.54%). Both of these variations in weld metal chemistry would promote reduction in hardenability and an increased tendency to form a higher temperature ferrite product on cooling. The resulting microstructure showed increases in the amount of large blocky grain boundary ferrite and decreases in the amount of Widmanstätten ferrite with increasing FeO content. The inclusion volume fraction was found to increase with the FeO addition and thus with weld metal oxygen content.

The SiO_2 - MnO - CaF_2 flux system produces weld metal oxygen contents lower than those achieved with eutectic manganese silicate flux. In reducing the weld metal oxygen content from 900 to 600 ppm with CaF_2 additions (0 to 60%) to the manganese silicate flux the weld metal microstructure changed from primarily proeutectoid ferrite with some patches of Widmanstätten ferrite to large fractions of acicular ferrite (27). The weld metal manganese content remained constant (0.95%) and thus, these microstructural variations can be attributed to the weld metal oxygen content. A decrease in inclusion fraction was observed with increased CaF_2 addition.

These results suggest that nickel, chromium and molybdenum slag additions do not alter the pyrometallurgical manganese reactions for the FeO-MnO-SiO_2 flux systems. There were also moderate losses in the chromium in the weld metal which correlated well with reduction in the weld metal oxygen content. In conjunction with the loss of these elements, the lowest weld metal hardness values were observed in this flux system.

The $(40\%)\text{SiO}_2\text{-MnO-CaO}$ system had the greatest loss in weld metal chromium and molybdenum contents, but retained a high manganese content. Weld metal manganese variation is consistent with the MnO activity known for this flux. Weld metal hardness values associated with this system were much higher than those of the $(40\%)\text{SiO}_2\text{-MnO-FeO}$ system.

The $(40\%)\text{SiO}_2\text{-MnO-CaF}_2$ system indicated a loss of manganese with increasing CaF_2 additions but no loss of chromium or molybdenum in the weld metal. This system had slightly higher weld metal hardness values than the $\text{MnO-SiO}_2\text{-CaO}$ system. The variation in hardness in the welds made using the different flux systems is believed to reflect the difference in the amount of martensite present. The variations in high strength steel weld metal composition observed for the welds made with these different fluxes, wires and welding parameters illustrated the necessity of selecting the proper combination of flux-wire-welding parameters if reproducible high integrity weld metal is to be achieved.

The oxide inclusions were found (20,21) to be of spherical shape, suggesting they were already present prior to solidification. Further, these inclusions were found to be segregated to the interdendritic cellular space during solidification. Thus, the distance between the rows of inclusions is a measure of the delta ferrite cell spacing. Using a special etch for the austenitic grains, it becomes apparent that each prior austenite grain has been made from many delta-ferrite cellular grains. The resulting microstructure leaves a variety of different nucleation sites for alpha ferrite both within the austenitic grain and at the grain boundary. It is not surprising that there is a variation in the type of ferrite formed, depending on the degree of supercooling. Reducing the weld metal oxygen content will reduce the number, size, and spacing of aligned inclusions, and thus increase the degree of supercooling by reducing the number and size of the nucleation sites.

An apparent observation on electron micrographs of the weld metal is that each ferrite grain appears to have a spherical oxide inclusion in it. There is evidence that the ferrite nucleates on inclusions and rejects carbon during growth to the remaining austenite. When sufficient supercooling is achieved, the remaining high-carbon austenite may even transform into extremely fine pearlite.

The ferrite products were examined more closely using light microscopy and TEM techniques and showing that each lath of acicular ferrite is truly a product of inclusion nucleation. It was observed that welds made with different fluxes but which have the same weld

and differences were experienced at both the upper and lower shelves of a toughness versus temperature plot even though no apparent microstructural difference were seen at the optical microscopy level for welds made at this heat input. Differences ,however, can be seen with electron microscopy. A larger number and a finer distribution of inclusions were experienced by the high oxygen welds. The fracture surfaces also indicated different fracture paths for the high (400 ppm) and low (200 ppm) oxygen welds. This work suggests that high performance steel weldments need to be characterized with magnification typical of electron microscopy.

2.9 The Influence of Submerged Arc Welding Fluxes on AISI 4340 Steel Weld Metal Microstructures

The effect of flux composition on weld metal microstructure and composition was investigated for submerged arc AISI 4340 steel weldments (25). Three different reagent grade welding flux systems were investigated: $\text{MnO-SiO}_2\text{-FeO}$, $\text{MnO-SiO}_2\text{-CaF}_2$, and $\text{MnO-SiO}_2\text{-CaO}$. The silica content of each flux system was held constant at 40 weight percent. Additions of FeO , CaF_2 , and CaO were made in five weight percent increments to a maximum of 60 weight percent, in each of the respective systems. These additions were made at the expense of MnO .

Chemical analysis was performed on all the AISI 4340 steel welds made with the various fluxes was achieved. This investigation determined the pyrometallurgical behavior involved between these fluxes and AISI 4340 steel and compared these results with behavior

metal oxygen content, have a different number and size distribution of inclusions. The same number and size distribution of weld metal inclusions, not necessarily constant weld metal oxygen, will give similar weld metal microstructure.

Quantitative metallography was also performed (22) on low carbon steel samples made with $\text{CaO-CaF}_2\text{-SiO}_2$ welding fluxes, in particular along the $\% \text{SiO}_2 / \% \text{CaO} = 1$ line, which showed a variation of weld metal oxygen content but held weld metal silicon and manganese content. The weld metal oxygen varied from 200 to 450 ppm oxygen. These welds were made with a heat input of 1.84 KJ/mm and the resulting microstructure was a mixture of acicular ferrite and grain boundary (veining) ferrite. With an increase in weld metal oxygen, the amount of grain boundary ferrite or veining increase from 0 to 10 percent. Both the amount and distribution of grain boundary ferrite are important to mechanical properties. Veining should be held to a minimum to maximize toughness. The relationship between proeutectoid ferrite veining and toughness is not very easy to quantify, since it depends on the orientation of the veins with respect to the crack propagation direction. It was also found that decreasing the weld metal oxygen content below 150 ppm for these welds made at this heat input produced an aligned ferrite or bainitic microstructure. This work suggests that there is an optimum weld metal oxygen content for a given manganese and silicon content to achieve the best properties.

Welds were also made with $\text{CaO-CaF}_2\text{-SiO}_2$ fluxes and with a heat input of 3.3 KJ/mm. Fracture toughness was measured on these welds

with AISI 1020 steel weldments. Also, the nature of the phase transformations, microsegregation and inclusions in the weld metal was characterized.

Macrohardness and microhardness measurements were made on transverse sections of the AISI 4340 weld metal. Light microscopy and transmission electron microscopy were used to examine the weld metal microstructure. A light vein-type microstructure was observed dispersed throughout the darker etching matrix. The veins were found to be martensite and the matrix was upper bainite. TEM analysis revealed that the weld metal matrix consisted of ferrite laths with elongated carbide particles between them, characteristic of upper bainite. The CCT diagram for AISI 4340 steel predicts a completely martensitic microstructure for the high cooling rate associated with welding. Microsegregation of the hardenability agents is believed to be responsible for the bainitic microstructure. Microprobe analysis did not find segregation of Ni, Cr, Mn or Mo. Apparently it is carbon segregation during solidification that causes the martensite and bainite banding in the weld metal. It is expected that this weld metal is characteristic of weld metal resulting from filler materials of the 80 to 100 ksi yield strength range; such as HY80 steel.

AISI 4340 steel welds made using the (40%) SiO_2 -MnO-FeO flux had weld metal manganese variation which is consistent with known MnO activity for the slag system. The weld metal manganese behavior was found to be identical for both the AISI 1020 and 4340 steels.

2.10 Effect of Shield Gas Oxygen Activity on the Ferrite Content and Morphology of Gas Metal Arc Welded Microalloyed HSLA Steel

Previous investigations have correlated the ferrite transformation kinetics and subsequent morphology to the weld metal inclusion content and oxygen content of the weld fusion zone. The submerged arc process, which is accomplished under a flux, produces weld metal which is influenced by flux metal pyrometallurgical reactions which occur during welding. This study was designed to determine the effect of oxygen and carbon content alone without the influence of the complex chemistry of the welding flux (26). By varying the oxygen activity of the shielding gas in the gas metal arc welding (GMAW) process, the effect of oxygen alone can be analyzed. It is anticipated that with the thorough investigation of gas metal arc weld metal chemistry and microstructure as a function of shielding gas content, information obtained from the previous investigations on submerged arc weld metal composition and microstructure can be better understood. Also, the determination of the transferability of microstructural interpretation learned from SAW to the GMA Welding technology would be a major contribution since there has been more comprehensive investigations into the pyrometallurgical behavior associated with submerged arc welding.

In this investigation, ninety welds were produced using fifteen different shielding gas contents (Ar-O_2 and Ar-CO_2), two welding wires with substantially different deoxidant contents, and three separate heat inputs. The base metal was United States Steel X-70 plate. Two

welding wires were selected, E70S6, the high deoxidant content wire, and E70S3.

The results showed that shield gas oxygen activity can substantially affect the final weld metal ferrite morphology. Increasing oxygen activity tended to enhance the grain boundary ferrite content, as well as alter the general ferrite morphology. However, there were some secondary effects of the heat input on that ferrite morphology. Decreasing the cooling rate resulted in an increased grain boundary ferrite content. This investigation determined an optimum shielding gas composition for a specific welding wire and heat input range to achieve low carbon steel weld metal with the complete acicular ferrite microstructure. Also, a new mathematical expression for weld metal composition has been determined to correlate the weld metal microstructure. The role of inclusions was described by an effective oxygen, O_{eff} , expression.

$$O_{eff} = (wt\% O) + 1/2(wt\% Si)$$

and the solid solution hardenability factor. The influence of hardenability was described by plotting the weld metal manganese content on effective oxygen versus manganese plot. These plots were found successful in understanding and predicting low carbon steel weld metal microstructure and properties.

2.11 A Method to Field Cut Stainless Steel With a Flux Related Arc-Cutting Process

Penetration of bead on plate welds obtained with FeO-MnO(40%)-SiO₂ fluxes was shown to increase with increasing additions of FeO for both AISI 1020 and 4340 steels (13). This general increase in penetration was related to a confining effect of the weld bead by the flux, which corresponds to an increase in heat input per unit area. Penetration obtained with welding fluxes containing 40-55 wt.% FeO, on AISI 4340 steel only, exceeded the thickness of the 1/2 inch (12.7 mm) steel plate forming a thin cut with excellent kerf (23). Similar cuts were also performed on type 304 stainless steel plates with thicknesses up to 3/4 inches (19 mm).

The fact that normal bead morphology was obtained with 0-40 and 60 wt.% FeO on AISI 4340 steel and that cutting was never observed for AISI 1020 steel, suggests that the additional heat input required to cut through the plate was provided by an exothermic reaction involving chromium. It is also known that high FeO contents in the flux can promote high weld metal oxygen contents; weld metal oxygen levels above 1500 ppm have been reported. If the high weld metal oxygen content is primarily involved in this cutting process, it is difficult to explain the lack of cutting with the 60 wt.% FeO additions to the flux. Since chromium is a major alloying element in both AISI 4340 steel and type 304 stainless steel, possibly a thermit reaction

involving the oxidation of chromium and reduction of iron oxide in the manganese silicate flux can explain the apparent excess local heat. Thermodynamic calculations suggest numerous possibilities of flux-metal reactant combinations which can give such highly exothermic behavior. The role of MnO additions is not clear.

This thermit approach based on the proper welding flux formulation may be useful in making cutting shielded metal arc electrodes for cutting stainless steel (23). A non-mechanical cutting process for stainless steel is a very valuable concept for field maintenance and assembly of stainless steel sections and parts.

2.12 Investigation of the Thermal and Metallurgical Characteristics of Non-Vertical Electroslag Welds

The electroslag welding process (ESW) has traditionally been performed in a vertical orientation. Problems of containing the large molten pool of flux and metal as well as positioning the electrode are less severe when the process is in the vertical position; however, due to intention or accident, that is not always the case. Consequently, this investigation was concerned with certain of those metallurgical and thermal aspects of electroslag welds which might be affected by having a non-vertical weld axis (12,15).

The symmetry associated with the thermal processes of electroslag welding is altered by the inclination of weld axis. The electroslag welding process, and in particular non-vertical electroslag welds are quite sensitive to welding parameters. Quite drastic anisotropy of the heat affected zone width and weld penetration was found to result from misalignment of the weld axis only slightly from vertical. In addition, the resulting anisotropy of heat distribution in small angle welds is much more sensitive to welding parameter values than in larger angle welds.

This study indicated that radiation heat transfer from the flux pool surface appears to be significant for certain combinations of welding parameters. Preferential radiative pre-heating of the upper weld surface is probably a major cause of penetration and HAZ width anisotropy in non-vertical electroslag welds. Previous investigators have reported current increases monotonically with electrode velocity; however, the increase in current is proportionately less rapid than the increase in electrode velocity for a given voltage. In addition, this observation was quantified empirically to show that the square of the current appears to vary directly with electrode velocity and inversely to voltage; a result subsequently confirmed by other investigations of ESW.

The electroslag welding process is quite applicable to situations in which the weld axis is inclined from vertical. The limitation of 10 to 15 degrees imposed by Paton is far too restrictive, and welds can be performed at angles of inclination of 60

degrees or possibly greater with satisfactory penetration. However, the "window" of current values allowable at a given voltage for high angles of inclination may be reduced.

2.13 Austenitic Welding Consumables for Ductile Iron

Three Studies in the welding of ductile iron have been performed. First, the microstructural and mechanical properties of single- and multi-bead weldments produced by submerged arc welding using flux additions of ferromagnesium, ferrosilicon, and graphite was investigation (1,2). These graphitization and nodularization additions to a neutral flux produce ductile iron weldments which have demonstrated excellent properties.

The second investigation determined the feasibility of replacement of the traditional Fe-55Ni austenitic welding consumable for ductile iron with a new consumable system based on Fe-Ni-Mn alloys. This effort has been highly successful and has discovered that manganese additions to the weld pool can produced welds with weld metal of lower hardness than welds made using the 55% nickel wire. The softest welds produced in this investigation have a hardness of $R_p 83$, suggesting excellent machinability. Even more desirable behavior has been observed by using a combination of nickel and manganese flux additions, which for certain composition gives an excellent thermal expansion match with ductile iron. The cracking tendencies of the fusion line has been minimized by taking advantage of the low-melting point of some Mn-Ni-Fe filler metals. The

microstructure for these Fe-Mn-Ni-C weld metal specimens were completely characterized. A patent application has been submitted on optimum Fe-Ni-Mn filler metal compositions. This new filler alloy reflects a major reduction in nickel content from present commercial high nickel cast iron filler materials.

In the third investigation, forty ductile iron welds were made with various Fe-Ni-Mn-Cu-C welding consumable compositions (28). Weld metal composition and microstructure were analyzed. The effort is to reduce the nickel content of the welding consumable used for cast iron with both copper and manganese additions. The weld metal composition was systematically varied by making metal powder additions to a submerged arc welding flux and bead-on-plate welding onto ductile iron. Ductile iron welding consumables with less nickel and manganese contents were achieved by these copper additions. Alloy ranges which produce acceptable weld metal hardness and no cracking were determined and reported. The weld metal thermal expansion for this new alloy system is not as desirable as found with first the Fe-Ni-Mn-C alloy system.

The determined thermal expansion mismatch of this Fe-Ni-Mn-Cu-C weld metal alloy with ductile iron may suggest that cracking problems will arise with the use of this consumable system for applications which experience thermal cycling service or multiple pass welding practice. Further work is required to determine if there are limitations for this new ductile iron welding consumable system.

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5.0 Bibliography

The bibliography is the same list of references as given in Section 3.0, the "List of publications and technical reports published during this contract."